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R. R. Busby
U.S. Army Engineer Research and Development Center, ryan.busby@us.army.mil

D. L. Gebhart
U.S. Army Engineer Research and Development Center

H. A. Torbert
United States Department of Agriculture–Agricultural Research Service

J. O. Dawson
University of Illinois at Urbana-Champaign

G. A. Bollero
University of Illinois at Urbana-Champaign

See next page for additional authors

Authors
R. R. Busby, D. L. Gebhart, H. A. Torbert, J. O. Dawson, G. A. Bollero, K. N. Potter, and D. R. Curtin

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Effects of a New Waste-Processing By-product on Soil and Vegetation at Fort Campbell, Tennessee

R. R. BUSBY,[1] D. L. GEBHART,[1] H. A. TORBERT,[2] J. O. DAWSON,[3] G. A. BOLLERO,[4] K. N. POTTER,[5] AND D. R. CURTIN[1]

[1]U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, Illinois, USA
[2]U.S. Department of Agriculture–Agricultural Research Service, National Soil Dynamics Laboratory, Auburn, Alabama, USA
[3]Department of Natural Resources and Environmental Sciences, University of Illinois, Urbana, Illinois, USA
[4]Department of Crop Sciences, University of Illinois, Urbana, Illinois, USA
[5]U.S. Department of Agriculture–Agricultural Research Service, Grassland Soil and Water Research Laboratory, Temple, Texas, USA

A garbage-processing technology has been developed that sterilizes and separates inorganic and organic components of municipal solid waste. A study was initiated to evaluate the uncomposted organic by-product of this process as a soil amendment for establishing native prairie grasses on disturbed Army training lands. The waste was incorporated into a silt loam soil at Fort Campbell Military Reservation in the central United States. The waste material was applied at rates of 0, 4.5, 9, 18, and 36 Mg ha^{-1} and seeded with native prairie grasses to assess its effects on vegetation for two growing seasons, with an additional unseeded control treatment for comparison to natural recovery. Treatments receiving the highest rate of application had significantly more native grass basal cover and percent composition than the controls. Plant phosphorus accumulation increased significantly with increasing pulp application. Soil phosphorus and lead concentrations increased in the top 10 cm of the highest application rates where pulp was mixed in the soil. Because minimal environmental effects were detected and the pulp improved perennial grass establishment and nutrition at the 36 Mg ha^{-1} rate, land application should be considered a viable and beneficial alternative to current waste-management practices.

Keywords Heavy metals, municipal waste, nutrient immobilization, plant establishment, soil restoration

Introduction

A process that facilitates the rapid separation, volume reduction, and conversion of municipal waste into a sterile organic pulp has been developed. This system grinds

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Address correspondence to R. R. Busby, U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, P.O. Box 9005, Champaign, IL 61826, USA. E-mail: ryan.busby@us.army.mil

up the garbage, separates out metals, and uses a hydrolyzer with high-temperature and high-pressure steam to break molecular bonds and destroy pathogens (Bouldin and Lawson Inc. 2000). The material is then dried and the organic material, called Fluff®, is separated from the recyclable glass, metal, and plastic constituents by air classification. After processing, the waste pulp is unrecognizable as formerly consisting of garbage. The organic by-product from this process can be landfilled at a 70% reduction in volume or composted (Bouldin Corp., unpublished data, 2001). However, the resulting material may also be effective directly as a soil amendment to improve soil physical and chemical properties, thereby enhancing land rehabilitation efforts. Because most contaminants and pathogens have been removed, this material could bypass the composting process and eliminate the most negative aspects of large-scale composting: the time and facilities requirements and resulting problems with leachate, odors, pests, and pathogen exposure.

The U.S. Army generated more than 1.2 million metric tons of solid waste in the United States in fiscal year 2003 but has a limited number of landfills, increasing costs to ship garbage off post (Solid Waste Annual Reporting 2004). However, with almost 5 million hectares of land in the United States, including 73 installations with more than 4,000 hectares each, the Army has enough acreage to support large-scale land utilization of organic waste by-products (DoD 2001). Additionally, the Army is mandated by numerous federal, agency, and departmental laws to control water and air pollution, maintain ecosystem sustainability, protect native biological diversity, control the spread of exotic species on its training lands and promote beneficial reuse practices whenever possible. By diverting organic matter from landfills to degraded training lands, the Army could incorporate reuse of municipal waste into land management, decrease waste-disposal costs, and improve land rehabilitation efforts on Army training and testing ranges.

The purpose of this research is to evaluate the use of Fluff as a soil amendment to successfully rehabilitate damaged military training lands, which often lack sufficient topsoil, organic matter, and nutrients required for successful rehabilitation. This study is a test of the hypothesis that an undecomposed material such as Fluff is beneficial as an organic soil amendment that can aid in the establishment of native grasses. An analysis of carbon (C) and nitrogen (N) mineralization of Fluff when applied to soils indicates that decomposition is slow, resulting in significant immobilization of N for an extended period of time (Busby, Torbert, and Gebhart 2007). Perennial warm season grasses, such as those native to the tallgrass prairie of North America, are well adapted to harsh environmental conditions, giving them a competitive advantage in poor soils (Jung, Shaffer, and Stout 1988; Levy, Redente, and Uphoff 1999; Skeel and Gibson 1996; Wilson and Gerry 1995). These grasses are used abundantly in reclamation, as they develop extensive root systems that penetrate deep into soils, providing a very effective safeguard against erosion (Drake 1983). Although these species are highly suited to conservation plantings, establishment is a significant barrier to successful utilization, as weedy species can easily overtake them and cause failure, especially in N-rich soils (Launchbaugh 1962; Warnes and Newell 1998; Brejda 2000). To overcome weed competition, addition of C amendments to immobilize soil N have shown promise, as native vegetation can benefit greatly from N-limiting conditions (Paschke, McLendon, and Redente 2000; Wilson and Gerry 1995; McLendon and Redente 1992).

On marginal lands such as degraded training areas, organic amendments such as waste pulp can be beneficial when used to enhance vegetation establishment. The increased soil organic matter should increase the soil water-holding capacity and pH, lower soil bulk density, and provide a slowly available source of nutrients. It is hypothesized that in the first season the amendment will begin decomposing and immobilize nutrients already present in the soils, thereby reducing weed competition and allowing slower-growing native grass species to gain a foothold. In subsequent years, it is believed that further decomposition of Fluff will result in mineralization of nutrients and concomitant increases in biomass and decreased species richness with reduction of weedy species as seeded native species become dominant.

Materials and Methods

Initial Fluff Analysis

Prior to any experimentation, the waste by-product was intensively analyzed for levels of 184 regulated compounds, including 11 heavy metals, 113 semi-volatile organic compounds, and 60 volatile organic compounds to determine any potential regulatory limitations. Analyses of toxicity characteristic leaching procedure (TCLP) volatiles, TCLP semi-volatiles, TCLP heavy metals, total organic halogen content (TOX), and low-resolution dioxin content were performed by PDC Laboratories (Peoria, Ill.), a U.S. Environmental Protection Agency (EPA) certified laboratory for Tennessee, using EPA methods SW846-8260, 8270, 1311, 9076, and 8280, respectively (U.S. EPA 1998). Only nine heavy metals, three semi-volatile organic compounds, and three volatile organic compounds were detected. The detected organic compounds (acetone, methylene chloride, toluene, di(2-ethylhexyl)phthalate, di-n-butyl phthalate, and di-n-octyl phthalate) are regulated in either the Clean Water Act or the Clean Air Act because of risks associated with workplace exposure and concentrated industrial effluent. However, because of their volatile chemical nature and rapid turnover in the environment, they pose very little risk at the concentrations found in the Fluff, especially when incorporated into the topsoil, and therefore are not regulated for this purpose.

Limits have been established for land application of heavy metals in biosolids, and these existing standards were used to assess metal loading of the by-product in the absence of a similar compost standard (*U.S. Code of Federal Regulations* 1999). A comparison of pulp heavy-metal concentrations and EPA biosolids limits for maximum metal concentrations, maximum annual soil metal loading, and maximum cumulative soil metal loading are presented in Table 1. In comparing metal concentrations in the pulp to the biosolid ceiling limits, it was found that all pulp metal concentrations were at least an order of magnitude less than their respective ceiling limits. The pulp metal concentrations were used to calculate maximum annual and cumulative application rates for the pulp, where lead (Pb) was found to be the contaminant of primary concern. Annually, this limit would be reached with an application rate of 229 $Mg\,ha^{-1}$. The maximum cumulative pulp application was found to be 4587 $Mg\,ha^{-1}$, or 20 repeated applications at the maximum annual limit. However, other factors would most likely preclude achieving these rates because of material and land availability, transportation, and incorporation constraints. Agriculturally significant properties of the Fluff are presented in Table 2. Fluff has a near-neutral pH and C/N ratio around 30, and research indicates it decomposes slowly (Busby, Torbert, and Gebhart 2007).

Table 1. Comparison of pulp heavy-metal concentrations with U.S. EPA limits for biosolid application

Metal	Pulp ($mg\,kg^{-1}$)	Biosolid ceiling limits ($mg\,kg^{-1}$)[b]	Biosolid annual loading rate limits ($kg\,ha^{-1}\,yr^{-1}$)[c]	Calculated maximum annual pulp application rate ($Mg\,ha^{-1}\,yr^{-1}$)	Biosolid cumulative loading limits ($kg\,ha^{-1}$)[d]	Calculated maximum cumulative pulp application ($Mg\,ha^{-1}$)
As	<RL[a]	75	2	—	41	—
Ba	46.6	—	—	—	—	—
Cd	1.9	85	1.9	1000	39	20526
Cr	39.8	—	—	—	—	—
Cu	47.7	4300	75	1572	1500	31447
Hg	0.547	57	0.85	1554	17	31079
Ni	9.12	420	21	2303	420	46053
Pb	65.4	840	15	229	300	4587
Se	9.67	100	5	517	100	10341
Zn	234	7500	140	598	2800	11966

[a]Reaction limit.
[b]From 40 CFR Part 503.13, Table 1.
[c]From 40 CFR Part 503.13, Table 4.
[d]From 40 CFR Part 503.13, Table 2.

Table 2. Agriculturally significant pulp properties

Parameter	Value
pH	6.5
C/N	32
C (%)	39.8
N (%)	1.26
P ($mg\,kg^{-1}$)	1900
K ($mg\,kg^{-1}$)	2170
Ca ($mg\,kg^{-1}$)	13600
Mg ($mg\,kg^{-1}$)	1400
Fe ($mg\,kg^{-1}$)	2460
Mn ($mg\,kg^{-1}$)	130
Zn ($mg\,kg^{-1}$)	234
B ($mg\,kg^{-1}$)	35.0
Cu ($mg\,kg^{-1}$)	47.7
Co ($mg\,kg^{-1}$)	2.00
Na ($mg\,kg^{-1}$)	5169

Grasses were selected for the land application study based on previous research, suitability, availability, cost, and photosynthetic pathway. Three C4 grasses [*Andropogon gerardii* (big bluestem), *Panicum virgatum* (switchgrass), and *Sorghastrum nutans* (indiangrass)] and one C3 grass [*Elymus virginicus* (Virginia wildrye)] were selected. Germination tests prior to the field study indicated that low application rates had no effect on germination, but pure pulp was too hydrophobic to be an effective germination medium (Busby 2003).

Study Site

The field study was carried out in north-central Tennessee at Fort Campbell Military Reservation (36° 59′ N latitude, 87° 61′ W longitude) on an abandoned hay field fallow for several years and currently used for Army training activities. The climate is humid subtropical with an average temperature of approximately 14 °C and annual precipitation of 1250–1350 mm spread almost evenly throughout the year. Soil at the site was a Sengtown silt loam (fine, mixed, semiactive, thermic, Typic Paleudalfs) (Soil Series Classification Database 2004; Soil Survey of Montgomery County 1975).

Experimental Design

The Fort Campbell land-application study commenced in late spring 2002 after mechanical removal of existing vegetation in the study plots. Application rates of 0, 4.5, 9, 18, and 36 Mg of pulp per hectare dry weight were selected. Controls consisted of both seeded and unseeded treatments to assess differences between natural recovery and seeding following disturbance. The study site consisted of four replications blocked by slope with 18.6-m^2 plots and 3-m unseeded buffer strips between blocks. The pulp was hand weighed and spread, followed by two passes with a disc plow to incorporate it into the soil to a depth of 15 cm. Plots were then hand seeded at a rate of 22 kg ha^{-1} with a mix containing equal weights of pure live seed of the four selected grass species and cultipacked to produce good seed–soil contact. First-year data collection occurred in fall 2002. Second-year data were collected in late summer 2003. Data collection consisted of basal vegetative cover, plant species composition, aboveground biomass, plant chemical analysis, and soil chemical and physical property analysis.

Vegetation Sampling

Species composition and basal vegetative cover were measured using a 10-point frame (Sharrow and Tober 1979), with 200 random points taken per plot. Plant biomass was collected by clipping five random samples per plot to a height of 1 cm using 30- × 60-cm quadrats. Samples, which consisted of composite samples of all species present, were dried at 60 °C until weight loss was complete and then weighed (Bonham 1989). Composite biomass samples were analyzed by the USDA-ARS National Soil Dynamics Laboratory. Analysis was performed for total aluminum (Al), boron (B), barium (Ba), calcium (Ca), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), phosphorus (P), lead (Pb), silicon (Si), and zinc (Zn) with procedures outlined by Hue and Evans (1986) using inductively coupled plasma spectrophotometry (ICP 9000, Thermo Jarell-Ash Corp., Franklin, Mass.) and total N using a Leco CN 2000 analyzer (LECO Corp., Saint Joseph, Mich.) (Bremner 1996; Soltanpour et al. 1996).

Soil Analysis

Soil samples were collected and analyzed by the USDA-ARS National Soil Dynamics Laboratory. Two soil cores (3.8 cm diam.) were collected from each plot using a custom-made telescoping soil coring device assisted by a modified commercial hydraulic post driver mounted to the front of a small tractor. The tractor hydraulic system powered both the telescoping device and the post driver. Soil samples were obtained at depths of 0–5, 5–10, 10–20, and 20–30 cm for both years and 30–60 and 60–90 cm in year 2. Both samples from each plot were composited to give one soil sample for each depth measurement for each plot. Subsamples of the soils were dried (55 °C), ground to pass a 0.15-mm sieve, and analyzed for total N and C on a Leco CN 2000 instrument (Nelson and Sommers 1996). Soil samples were also analyzed for Mehlich III (Mehlich 1984) extractable Al, arsenic (As), B, Ca, cadmium (Cd), Cr, Cu, Fe, K, Mg, Mn, Na, nickel (Ni), P, Pb, sulfur (S), selenium (Se), and Zn, using inductively coupled plasma spectrophotometry (ICP 9000). In year 1, nitrate, ammonia, and total inorganic N were extracted with 2 M potassium chloride (KCl) and measured by standard colorimetric procedures using a Technicon Autoanalyzer 3 (Bran+Luebbe, Buffalo Grove, Ill.). Soil bulk density was measured in year 2 only at depths of 0–5, 5–10, 10–20, and 20–30 cm. Additional pH data were collected for both years in the top 30 cm (McLean 1982).

Statistical Analysis

Year and pulp application treatment effects on cover, diversity, composition, biomass, and plant chemical concentration as well as depth effects for soil chemical properties measured in both years were tested with repeated measures of analysis of variance using the PROC MIXED procedure in SAS along with interactions, and treatment and interaction effects for variables measured during only a single year were tested with analysis of variance using PROC MIXED (Littel et al. 1996; SAS Institute 2001). Measured variables not meeting the assumptions of analysis of variance were log-transformed and retested for normality and equal variance. Significant differences between means were tested using linear contrast statements at the 0.05 probability level. Means presented in the text are nontransformed.

Results and Discussion

Basal Vegetative Cover

One plot, the 9 Mg ha^{-1} treatment in block 1, was not analyzed because native grasses failed to emerge. Virginia wildrye was not analyzed separately because it did not provide enough data for individual analysis. In year 1, 32 species in 19 families were observed. In the second year, 36 species in 16 families were encountered, with 49 species in 24 families recorded for the entire study. Species were primarily agricultural weeds typical of early successional communities and seeded grasses.

Total basal vegetative cover differences were not significant across years or treatments. Annual grass and total annual cover were relatively unaffected by Fluff treatment but were significantly greater in the unseeded control treatment than in the 36 Mg ha^{-1} treatment at the 0.05 probability level. The 36 Mg ha^{-1} treatment had significantly more total perennial ($p < 0.05$), perennial grass ($p < 0.05$), and planted grass ($p < 0.05$) cover than both the seeded and unseeded controls. Big bluestem, indiangrass, and switchgrass cover were unaffected by treatment or year. Planted grass mean percent cover by pulp treatment is presented in Figure 1.

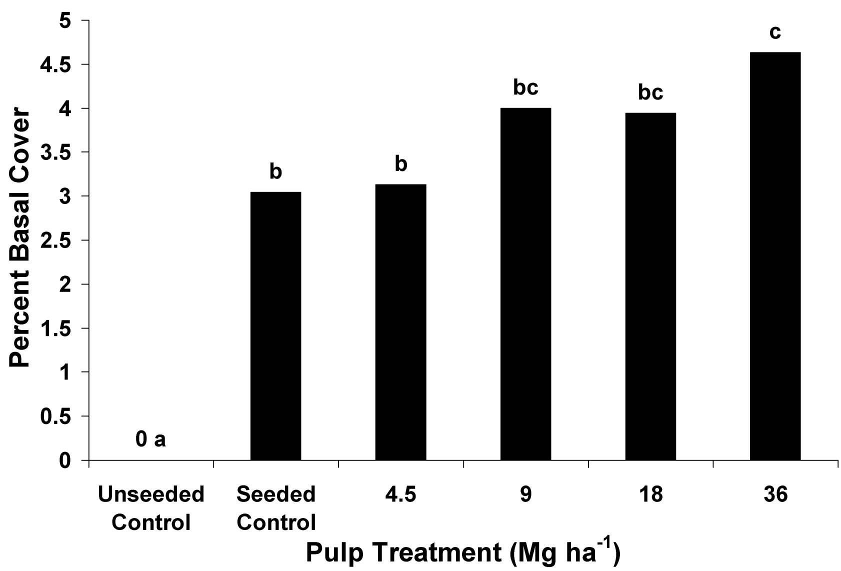

Figure 1. Planted grass mean percent basal cover by pulp treatment. Means with the same letter are not significantly different at the 0.05 probability level.

Weedy annual grasses were not affected at the level originally hypothesized. It was expected that annual weeds, with characteristic shallow root systems and intolerance to shading, would respond negatively to increased competition with taller, deeper rooted perennial prairie grasses. A previous study performed in Tennessee to assess the use of the same species of native warm-season grasses was not successful at obtaining adequate stands because competition from annual grass species (Graves et al. 1997). Even though annual grasses were unaffected in this study, the increases in switchgrass and big bluestem cover show a positive result of pulp application.

Percent Composition

Indiangrass ($p = 0.004$), switchgrass ($p = 0.02$), and total planted grass ($p = 0.001$) percent composition increased significantly from year 1 to year 2. Big bluestem percent composition was not affected by year. Pulp application rate had a significant effect on vegetation composition. The 36 $Mg\,ha^{-1}$ pulp treatment had significantly greater switchgrass ($p < 0.05$), big bluestem ($p < 0.05$), total planted grass ($p < 0.05$), and total perennial ($p < 0.10$) percent compositions than either control. Planted grass mean percent composition by pulp treatment is presented in Figure 2. Additionally, the high pulp rate had lower annual ($p < 0.10$) percent composition than either control. Indiangrass percent composition was unaffected by treatment.

Plant diversity remained constant throughout the study, in contrast with our hypothesis, but in early successional communities, diversity is naturally so low that differences during the time period of this study would be difficult to assess (Barbour et al. 1999). The resulting positive changes in percent composition of the planted grasses and reduction in annual percent composition in the high pulp treatment indicate that the pulp is having a desirable effect on vegetation composition and that these changes may be more noticeable at higher application rates.

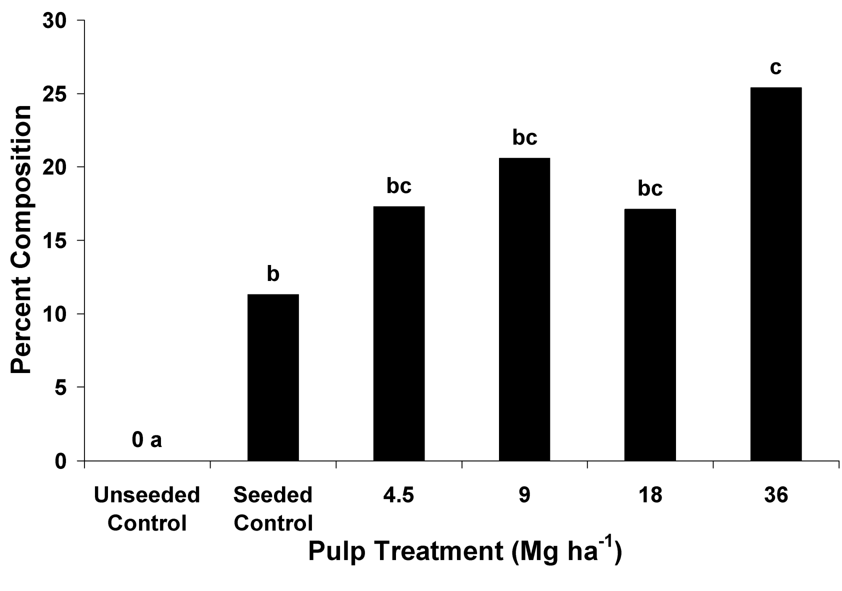

Figure 2. Planted grass mean percent composition by pulp treatment. Means with the same letter are not significantly different at the 0.05 probability level.

Based on the results of the composition and cover analyses, establishment of two of the three native warm-season prairie grasses was enhanced with pulp application rates of 36 Mg ha^{-1}. Indiangrass appears to be relatively unresponsive to the pulp, but switchgrass and big bluestem showed notable increases at the highest application rate. Because annual grass cover remained constant but its relative percent composition decreased, it can be concluded that the pulp was in some way beneficial to the prairie grasses but not inhibitory to weedy species during the first two growing seasons following application of up to 36 Mg ha^{-1}.

Biomass

Aboveground biomass indicated a significant treatment $\times$ year effect ($p = 0.01$) due to significant increases in biomass for all treatments across years except the unseeded control, which remained constant (Table 3). No significant differences in biomass were found between the pulp treatments and seeded control. The lack of change in biomass in the unseeded control plots compared to the seeded plots was most likely due to dominance by ruderal species in the unseeded control plots that typically lack the biomass found in the seeded perennial grasses.

Plant Chemical Analysis

Treatment had no effect on the majority of analyzed elements, but significant differences were found for shoot P concentrations ($p = 0.001$) (Table 4). Shoot P concentrations also exhibited a significant treatment $\times$ year effect ($p = 0.0079$) due to significant decreases in P concentrations from year 1 to year 2 in all treatments except the unseeded control, which did not change significantly at the 0.05 probability level (Figure 3). In year 1, the 36 Mg ha^{-1} treatment had a significantly greater P concentration than all other treatments and more than twice that of the controls. The 18 Mg ha^{-1} treatment had significantly more shoot P than the unseeded control in year 1. In the second year, shoot P levels in the 18 and 36 Mg ha^{-1} treatments were not significantly different from the unseeded control. Between years, there were no significant changes in plant P in any of the pulp treatments, but both controls increased significantly in P concentration from year 1 to year 2.

Table 3. Aboveground biomass by treatment over time

	Biomass (g m^{-2})	
Treatment (Mg/ha)	Year 1	Year 2
0 (unseeded)	430.1 b	400.7 b
0 (seeded)	449.1 b	674.5 a
4.5	243.6 c	544.7 a
9	231.5 c	646.4 a
18	356.7 bc	575.1 a
36	307.9 bc	655.7 a

Notes. Values represent means of 20 samples. Means with the same letter are not significantly different at the 0.05 probability level.

Table 4. Mean shoot concentrations of nutrients and other elements by pulp application treatments

Pulp treatment	Plant macronutrients					Plant micronutrients					Other accumulated elements						
(Mg ha^{-1})	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Cu (mg kg^{-1})	Zn (mg kg^{-1})	B (mg kg^{-1})	Al (mg kg^{-1})	Ba (mg kg^{-1})	Co (mg kg^{-1})	Cr (mg kg^{-1})	Pb (mg kg^{-1})	Si (mg kg^{-1})	Na (mg kg^{-1})
Unseeded	0.611	0.1008	1.2793	0.3855	0.1553	280.7	147.0	4.50	27.20	15.72	254.5	72.61	0.333	0.960	1.52	138.9	104.1
control	(0.059)[a]	(0.0189)	(0.0893)	(392)	(0.0064)	(70.9)	(11.1)	(0.77)	(2.39)	(1.10)	(65.6)	(8.75)	(0.112)	(0.477)	(0.42)	(16.1)	(4.9)
Seeded	0.719	0.0916	1.1760	0.3537	0.1412	250.5	121.6	3.87	23.94	14.83	236.9	68.22	0.306	0.840	1.780	122.2	117.7
control	(0.075)	(0.0095)	(1.009)	(406)	(0.0093)	(105.2)	(13.2)	(0.95)	(2.15)	(1.70)	(127.4)	(13.54)	(0.111)	(0.615)	(0.95)	(10.8)	(18.8)
4.5	0.756	0.0912	1.0470	0.4089	0.1469	284.2	142.5	3.18	26.65	14.87	276.0	80.69	0.230	0.604	1.97	142.8	104.0
	(0.041)	(0.0075)	(0.0795)	(308)	(0.0061)	(57.6)	(12.0)	(0.97)	(2.47)	(0.99)	(61.0)	(14.99)	(0.102)	(0.295)	(1.16)	(9.9)	(8.7)
9	0.844	0.1013	1.2320	0.4273	0.1672	330.8	146.0	4.95	28.58	17.61	335.2	70.46	0.355	0.603	2.04	146.3	111.5
	(0.074)	(0.0116)	(1.538)	(339)	(0.0116)	(87.9)	(15.4)	(0.73)	(3.31)	(2.46)	(100.6)	(10.48)	(0.130)	(0.331)	(0.81)	(8.3)	(12.6)
18	0.807	0.1181	1.1918	0.3636	0.1470	189.5	110.5	3.87	26.67	15.96	157.8	45.92	0.180	0.100	0.81	102.0	113.1
	(0.092)	(0.0102)	(1.025)	(373)	(0.0049)	(40.3)	(11.9)	(0.67)	(2.41)	(1.61)	(39.6)	(4.37)	(0.076)	(0.100)	(0.40)	(7.5)	(11.6)
36	0.876	0.1407	1.1876	0.3979	0.1455	213.7	115.5	4.07	29.60	16.25	203.7	53.32	0.165	<DL[b]	1.44	113.4	117.7
	(0.119)	(0.0106)	(0.0990)	(391)	(0.0094)	(54.2)	(11.8)	(0.92)	(3.25)	(1.30)	(62.8)	(5.86)	(0.072)		(0.83)	(5.3)	(14.7)

[a]Values represent means of eight samples. Standard errors are in parentheses.
[b]<DL = below detection limit.

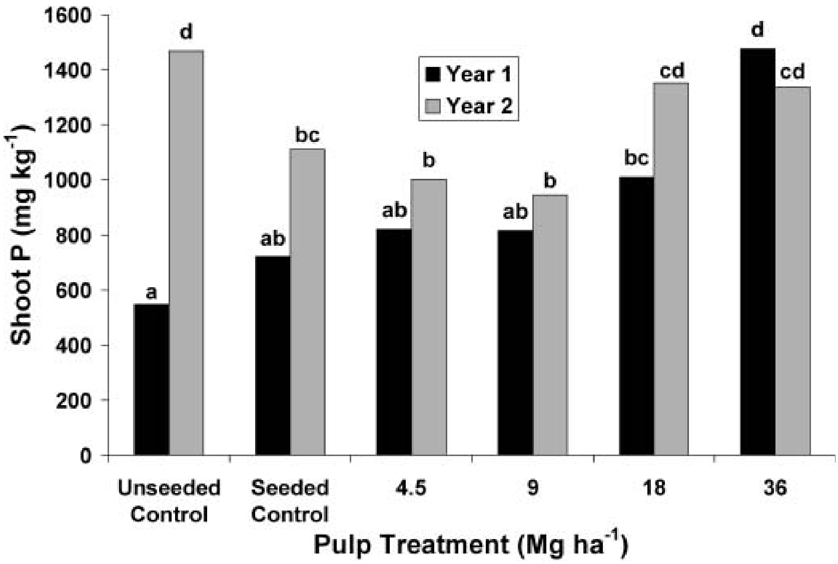

Figure 3. Mean plant P concentration by pulp treatment between years. Means with the same letter are not significantly different at the 0.05 probability level.

Plant K and P appeared to be deficient in some of the treatment plots compared to levels described in Munshower (1994) and Kabata-Pendias and Pendias (1992). Plant K samples below normal levels were randomly dispersed across treatments, and 88% of them occurred in the second year. The majority of plants collected for analysis were mature, and deficient K levels in mature plant tissues are common (Munshower 1994). Plant P levels follow a similar pattern as those of other macronutrients, with greater concentrations in young, actively growing tissues and apparently deficient levels in mature tissues. However, shoot P concentrations were not as randomly dispersed as those of K, and 70% of the deficient samples occurred in year 1. All control plots in year 1 had low P levels, and half of all seeded control samples in year 2 were deficient. The 4.5 and 9 Mg ha^{-1} treatments showed widespread deficiencies as well and were scattered across years. However, only two samples from the 18 Mg ha^{-1} treatment and none of the 36 Mg ha^{-1} samples showed low P accumulation, indicating a positive relationship between the high pulp application rates and plant P uptake (Figure 3).

Soil Analysis

In the top 30 cm, soil pH showed a significant treatment effect across years ($p = 0.04$) with a significantly lower unseeded control pH (5.32) than all other treatments (5.52–5.66) at the 0.05 probability level (Table 5). Few treatment effects were found for soil nutrients analyzed in the top 30 cm (Table 5). Soil C was significantly greater in the 36 Mg ha^{-1} treatment than in the unseeded control across years. Soil N was unaffected by treatment. Soil P ($p = 0.0002$), K ($p < 0.0001$), Ca ($p = 0.0054$), Mn ($p < 0.0001$), and Cu ($p = 0.0195$) showed significant pulp treatment effects (Table 5). Soil P also exhibited a significant treatment $\times$ depth interaction effect ($p = 0.0053$) due to the 36 Mg ha^{-1} treatment having significantly greater P concentrations than the unseeded control treatment in the 0- to 5-and 5- to 10-cm depths at the 0.05

Table 5. Mean soil chemical properties by pulp application treatments

Pulp treatment (Mg ha^{-1})	pH	C (%)	N (%)	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	S (mg kg^{-1})	B (mg kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})	Na (mg kg^{-1})	Al (mg kg^{-1})	As (mg kg^{-1})	Cd (mg kg^{-1})	Cr (mg kg^{-1})	Ni (mg kg^{-1})	Pb (mg kg^{-1})	Se (mg kg^{-1})
Unseeded control	5.32 b[a]	0.909 b	0.091 a	0.566 b	91.77 b	874.2 a	203.67 a	37.05 a	0.375 a	0.878 a	78.34 a	35.16 b	3.694 a	261.06 a	888.38 a	7.197 a	0.059 a	0.119 a	0.184 a	0.378 c	0.313 a
Seeded control	5.60 a	1.035 ab	0.102 a	1.938 ab	123.56 a	1021.2 b	190.15 a	28.05 a	0.500 a	0.894 a	75.16 a	63.17 a	2.581 a	243.84 a	784.47 c	6.159 b	0.059 a	0.128 a	0.200 a	0.494 c	0.341 a
4.5	5.52 a	1.009 ab	0.098 a	1.097 ab	126.21 a	1028.0 b	196.73 a	34.13 a	0.469 a	0.941 ab	77.16 a	60.94 a	3.709 a	252.41 a	833.85 abc	6.481 b	0.044 a	0.125 a	0.191 a	0.425 c	0.375 a
9	5.57 a	1.095 ab	0.110 a	1.491 ab	139.70 a	1056.1 b	207.21 a	32.18 a	0.594 a	0.931 ab	77.73 a	70.64 a	3.713 a	251.97 a	845.77 ab	6.688 ab	0.063 a	0.138 a	0.163 a	1.053 bc	0.441 a
18	5.61 a	1.088 ab	0.108 a	3.363 a	110.82 ab	1044.5 b	194.73 a	33.11 a	0.500 a	1.169 bc	81.34 a	60.61 a	3.488 a	259.63 a	825.56 bc	6.588 ab	0.059 a	0.138 a	0.200 a	1.269 ab	0.419 a
36	5.66 a	1.139 a	0.110 a	2.534 ab	124.20 a	1036.4 b	194.22 a	32.80 a	0.500 a	1.206 c	80.54 a	66.17 a	3.425 a	256.50 a	817.52 bc	6.403 b	0.059 a	0.134 a	0.194 a	1.972 a	0.513 a

[a]Values represent means of eight samples. Means for each property with the same letter are not significantly different at the 0.05 probability level.

probability level. Also, the 18 and 36 Mg ha^{-1} treatments had significantly greater P concentrations in the top 10 cm than depths lower in their profiles at the 0.05 probability level, whereas soil P remained constant throughout the soil profile for all other treatments.

Few significant effects were observed for soil heavy metals. A significant pulp application treatment effect was observed for Pb ($p < 0.0001$), Al ($p = 0.0007$), and As ($p = 0.0022$) extracted with Mehlich III extractant (Table 5). Mean As concentration was significantly lower in the pulp treatments than the unseeded control at the 0.05 probability level, and Pb concentration increased approximately 1.5 mg kg^{-1} in the 36 Mg ha^{-1} treatment over the controls.

Soil Pb concentration also exhibited a marginal treatment $\times$ depth interaction effect ($p = 0.0784$). Significant differences between treatments at the 10- to 20- and 20- to 30-cm depths were not found, but at the 0- to 5- and 5- to 10-cm depths, the 36 Mg ha^{-1} treatment had higher statistically significant Pb levels than both controls and the 4.5 Mg ha^{-1} treatments at the 0.05 probability level (Figure 4). Within treatments, no significant differences were found between depths for the unseeded, seeded, and 4.5 Mg ha^{-1} treatments at the 0.05 probability level. However, in the 9, 18, and 36 Mg ha^{-1} treatments, Pb concentrations in the top 10 cm were significantly higher than their respective concentrations in the 10- to 30-cm depths.

At the 30- to 90-cm soil depth (analyzed in the second year only), significant treatment effects were observed for soil Ca ($p = 0.036$), K ($p = 0.008$), Zn ($p = 0.026$), Cu ($p = 0.011$), Al ($p = 0.035$), As ($p = 0.015$), and Ni ($p = 0.018$) (data not shown). Mean soil Ca concentrations at this depth were significantly greater in the 36 Mg ha^{-1} than all treatments except the 18 Mg ha^{-1} treatment. The unseeded control treatment had significantly lower mean soil K concentration at this depth than all other treatments except the 18 Mg ha^{-1} treatment. For Al, As, Cu, Ni, and Zn, the unseeded control treatments had significantly greater soil metal concentrations than the 36 Mg ha^{-1} treatments.

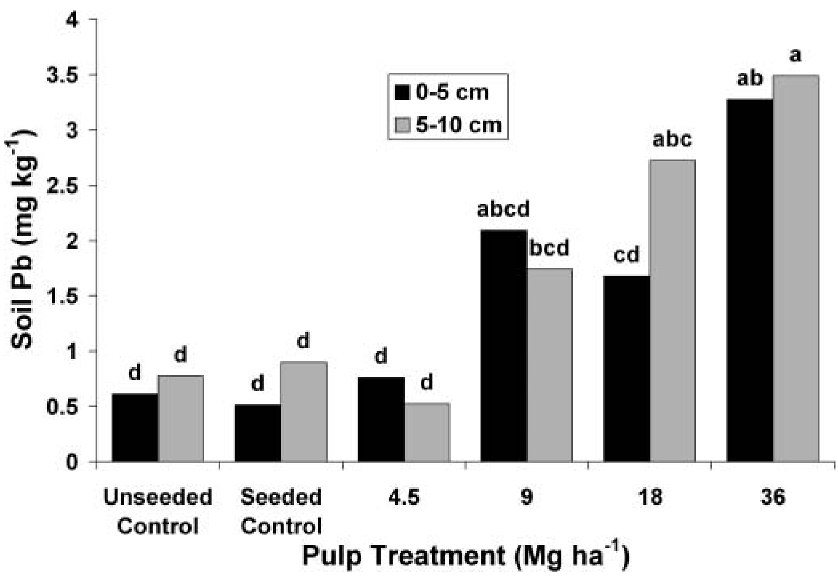

Figure 4. Mean soil Pb concentration by Fluff treatment between 0- to 5- and 5- to 10-cm depths. Means with the same letter are not significantly different at the 0.05 probability level.

The analysis of soil chemical properties indicates that pulp application can significantly increase available P in soils. The increase in extractable soil P in the highest application rates combined with a stable and sufficient level of plant P indicates that an adequate amount of labile P is supplied by pulp rates of $18\,\mathrm{Mg\,ha^{-1}}$ and higher. Whether the effect of increased plant P accumulation is a direct result of pulp supplied P or by some other mechanism is unknown. Because weedy plants usually respond better to fertilization than warm-season prairie grasses, this result may be due to increased mycorrhizal infectivity as weedy grasses did not diminish with increasing application rate but prairie grasses increased. A study conducted on iron mine tailings in Minnesota found that composted yard waste significantly increased vesicular–arbuscular mycorrhizal infectivity compared to inoculation using some of the same species planted in this study and that available P increased more in the plots amended with the compost than with fertilizers (Noyd et al. 1995; Noyd, Pfleger, and Norland 1996). However, given that soil P levels only increased in the depths where pulp was incorporated, decomposition of the Fluff and subsequent mineralization of P was most likely responsible, regardless of the effect of pulp on mycorrhizal infection. The added P from the pulp may have promoted N immobilization, which would affect annual species more than the planted perennial grasses, as the prairie grasses are much more efficient at nutrient utilization (Brejda 2000). This would explain why plant shoot P concentration, soil P concentration, cover of planted grasses, and pulp application were all directly related but soil and shoot N concentrations and annual grass cover were unaffected.

Although soil Pb levels increased significantly from a statistical standpoint in the upper profiles of the high pulp rates, this is not a significant change from a regulatory standpoint and amounts to a net increase of approximately $1.5\,\mathrm{mg\,kg^{-1}}$ in the top 30 cm of the highest pulp application rate over the controls. Additionally, both P and Pb only increased in the top 10 cm, where the pulp was incorporated, indicating that no movement into the lower soil profile was occurring after two growing seasons. Because Pb is very tightly bound by soil organic matter, it does not readily leach through the soil profile and is largely unavailable for plant uptake (Kabata-Pendias and Pendias 1992).

The lack of treatment effects on soil C and N, soil pH, and soil bulk density indicate that pulp treatments were too low to effectively alter the most critical soil properties. The hypothesized effects of the pulp on changes in soil properties were not realized but would probably be found in greater application rates. The material has a high undecomposed C content, a neutral pH compared to the soil pH of 5.6, and very low density compared to soil.

Although few changes were observed in soil properties, application of pulp appeared to create an environment favorable to establishment of perennial native grasses. In military training areas consisting of vast acreages of land, $36\,\mathrm{Mg\,ha^{-1}}$ can divert a considerable amount of garbage from landfills and incinerators while at the same time accelerating recovery on land receiving training disturbances. Given that there were few changes in soil chemical properties and increased cover of desirable vegetation, application rates much greater than $36\,\mathrm{Mg\,ha^{-1}}$ are plausible, providing a larger sink for this material. This could be accomplished through single or multiple applications, although long-term effects from large-scale or multiple applications on the environment remain unknown.

Conclusion

The primary objective of this study was to assess the reuse of an undecomposed organic municipal waste by-product according to environmental criteria. No negative effects were found. The material, which could result in a 70% reduction in the household waste stream when land applied, yielded several positive results when used to establish native grasses on disturbed Army training lands. The $36\,\mathrm{Mg\,ha^{-1}}$ pulp application benefited native grass establishment and increased basal cover of two of the four planted perennial grasses. Plant P accumulation was also increased by the $36\,\mathrm{Mg\,ha^{-1}}$ treatment. Soil concentrations of many metals and nutrients were unaffected by pulp addition. Soil Pb and P concentrations both increased with increasing rates of application. However, the increase in Pb was insignificant ($1.5\,\mathrm{mg\,kg^{-1}}$ for the greatest pulp rate) with respect to established regulatory limits. The increase in soil P concentrations in the high pulp rates alleviated an apparent P deficiency in the study-site soils.

Based on these findings, it would be beneficial to use this material as a soil amendment for reestablishing perennial warm-season grasses on disturbed acidic soils with limited P availability. Rates of at least $36\,\mathrm{Mg\,ha^{-1}}$ should be used to achieve noticeable benefits to seeded species, although the upper limit for these benefits has not been determined. The annual limit of pulp application from a regulatory standpoint based solely on levels of Pb in the material compared to allowable levels in biosolids application would be approximately $230\,\mathrm{Mg\,ha^{-1}}$ $\mathrm{year^{-1}}$, with a cumulative limit attained around $4600\,\mathrm{Mg\,ha^{-1}}$. However, because of logistical challenges and the potentially negative effects on soil physical and chemical properties, these rates would not be advisable. If the greatest application rate used in this study were repeated once every 5 years, the limit would be reached in about 650 years. However, to maintain native grass stands, the annual application rate would be significantly less because of potential negative compositional changes that could result from N deposition over time.

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